Challenges and Solutions for Distance Elements Protecting Transmission Lines With Tapped Loads

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Abstract—**In this paper, we discuss challenges of distance elements protecting subtransmission lines (typically 34.5 kV to 138 kV) with tapped loads.**

Typically, in subtransmission lines with tapped loads, the tapped load transformer impedance is significantly higher relative to the subtransmission line impedance. This impedance difference ensures distance elements that overreach the subtransmission line do not overreach for low-side faults. However, in scenarios where the subtransmission line is long and the tapped load is close to one terminal, there is a potential for distance elements that overreach the subtransmission line to also overreach for low-side faults. Traditionally, this security concern is addressed by either installing communications equipment at the tapped station to send a blocking signal to the transmission line relays or by reducing the reach of the overreaching distance elements. In cases where the reach is reduced, the end-of-line (EOL) faults are cleared by the subtransmission line relay time-overcurrent elements. The tradeoff for reducing the reach of the distance elements is delayed clearing of EOL faults.

In this paper, we provide solutions for both stepped distance and pilot scheme applications where the protected line is long and the tapped loads are located close to a relay terminal. These solutions allow the engineer to set the overreaching distance elements in the subtransmission line relays dependably and securely, while maintaining transmission trip times.

I. INTRODUCTION

Subtransmission lines operating between 34.5 kV and 138 kV with tapped loads are common in utilities to provide power to customers along the path of a subtransmission line. These tapped loads are connected to the subtransmission lines via a step-down transformer, and the isolation between them is provided by a circuit breaker, fuse, motor-operated disconnect (MOD), or a circuit switcher.

The tapped load creates protection challenges for various subtransmission line relay protective elements [1] [2]. In this paper, our focus will be on the challenges and solutions in applying distance elements (21) dependably and securely. As such, these challenges and solutions are applicable to not only subtransmission lines, but also transmission lines, even if it is unlikely to install a tapped load on lines operating at a voltage above 138 kV. Therefore, we will refer to transmission line protection for the remainder of this paper. We will discuss both stepped distance and pilot scheme applications.

II. TAPPED-LOAD LINES

A tapped load challenges protection principles applied on traditional two-terminal transmission circuits. When protecting these lines, it is important to understand the protection implemented at the tapped-load station to apply coordinating transmission line protection in these applications. Additionally, line sectionalizing is applied on tapped-load circuits presenting additional challenges to the protection scheme. In this section, we discuss different protection philosophies applied at tapped-load stations and the impacts sectionalizing has on pilot protection schemes. We also discuss how basic distance element protection is applied to these circuits.

A. Tapped-Load Station Protection

The protection implemented in the tapped-load transformer is of the most concern when maintaining coordination with transmission line relays. Tapped-load transformers can be protected with differential protection that offers high-speed clearing, but will always have a time-overcurrent backup to coordinate with downstream distribution feeders in the form of a 51 relay. In some applications, high-side fuses are the primary protection for tapped-load transformers. Any element set in the transmission line relay that can operate for faults past the transformer must coordinate with this backup overcurrent.

Time-overcurrent coordination between the phase time-overcurrent transmission line relays (51LP) and the transformer phase time-overcurrent relays (51TP) is somewhat challenging for low-side faults. For low-side faults, the 51TP will measure the total current contribution to the fault, while the 51LP relay will measure only its local terminal contribution to the fault. When the remote terminal is closed, the infeed from the remote terminal ensures that the 51TP will see more current than the 51LP, which aids in coordination between the two devices. However, the 51LP and 51TP must also coordinate when the remote terminal is open, which will lead to longer 51TP operation times than if the remote breaker is closed, and in turn, lead to higher 51LP time-dial settings to coordinate. If the protected line is relatively short, then the 51LP may still provide relatively fast protection for faults on the line while maintaining coordination for low-side faults. This is because line faults will produce much more fault current than low-side faults, which are limited by the transformer impedance. However, in long line applications, the 51LP can be quite slow to clear end-of-line (EOL) faults.

Line current differential relays often offer an overcurrent relay that can vectorially sum the contribution from each terminal (51LPT) to provide better coordination between the line relays and 51TP.

Most tapped loads are fed by delta-wye transformers, so a line ground time-overcurrent relay (51LG) will not see any ground current for low-side faults. Therefore, 51LG does not have any coordination concerns with tapped-load ground fault protection.

Traditional step distance protection can often be set so that it does not operate for faults beyond the transformer. This eliminates the need for time-based coordination between the transmission line relays and the tapped load, and it can greatly simplify fault studies. This also significantly reduces the time it takes to clear a line fault, especially EOL faults outside of a traditionally set zone 1 element reach.

B. Line Stepped Distance Protection

Stepped distance relies only on the local distance relay measurements using two distance element zones for 100 percent line fault coverage.

Zone 1 is an instantaneous tripping element. In applications of transmission lines with tapped loads, zone 1 must not overreach the remote terminal, nor the low side of any tapped load stations.

Zone 2 is an overreaching distance zone and operates with a time delay. Generally, a zone 2 distance element protecting a transmission line must reach beyond the remote terminal with margin to ensure adequate dependability. To prevent concerns with selectivity, zone 2 should also not reach past any tapped load. This allows a common time-delay setting for zone 2 (20 cycles) to coordinate with remote station zone 1 relays. If zone 2 does not overreach a tapped load, no further consideration is required to maintain zone 2 coordination.

However, if the transmission line is long, the tapped load is located close to the local line terminal, the transformer has large capacity, the remote transmission line terminal is a weak source, or a combination thereof, it may not be possible to dependably protect the line while maintaining security for low-side faults.

In these cases, zone 2 can be set to dependably protect the line while security for low-side faults is provided by communications equipment installed at the tapped-load location to send a blocking signal. This allows the transmission line relay to operate within 20 cycles for all transmission line faults. If the line terminal relay overreaches multiple tapped loads along the line, installing communications equipment at each tapped load is required and can become complex and costly.

C. Sectionalizing of the Line

Transmission lines with tapped loads are often sectionalized to maintain operational flexibility. For example, from Fig. 1, an operator can open Disconnect R if Breaker R needs to be taken out of service for maintenance, or if a permanent fault is located on the right side of the tap point. The tapped load is then fed from Bus S, making the transmission line radial.

When a line becomes sectionalized such that zone 1 covers up to the open switch point, all sectionalized line faults are cleared immediately. If a portion of the sectionalized line still falls outside of zone 1, then some faults will be cleared via zone 2 in a step distance scheme.

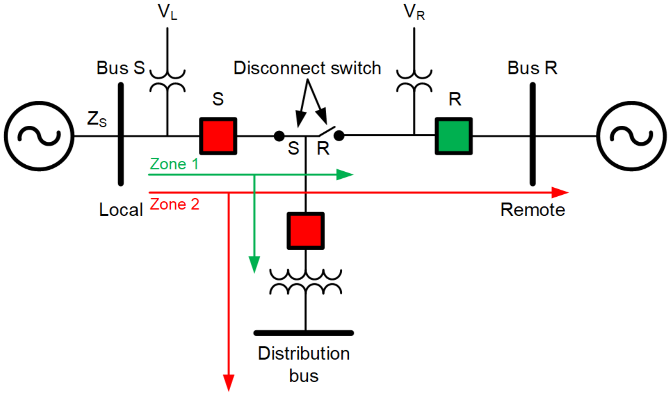

Fig. 1. Switching creates a radial line section.

D. Pilot Scheme (Directional Comparison Blocking)

Pilot schemes are applied to provide high-speed fault clearing for faults on the transmission line outside zone 1 reach. In pilot schemes, the local relay relies on remote relay measurements for fast overreaching distance element operation. In transmission lines with tapped load, the directional comparison blocking (DCB) pilot scheme naturally provides an improvement in fault-clearing speed for faults outsize of zone 1 reach even under line sectionalization conditions because reception of a block signal is not needed for fast zone 2 operation. If the line is fully intact and an external fault occurs, then the remote terminal will send a block signal to the local terminal to prevent a fast zone 2 operation.

The zone 2 reach in DCB schemes must not overreach the tapped load transformer to maintain security, unless a block is provided from the tapped load, just like in a stepped distance scheme. So, if fast line clearing is desired for 100 percent of a tapped-load line, the natural choice is to use a DCB scheme.

III. LIMITATIONS OF ZONE 1 AND ZONE 2 REACH

In general, troubles arise in setting 21 element reach when a tapped load is close to the local terminal with the remote terminal breaker open (RTO). When a fault occurs on the low side of a tapped-load transformer with RTO, the local relay will not have the benefit of remote infeed to increase the apparent impedance seen by the local terminal for low-side faults. Therefore, it is less likely the distance elements overreach the load-tapped transformer when the remote breaker is closed, and more likely with RTO.

Fig. 2 shows a system diagram where Z_L represents positive-sequence line impedance, Z_{TAP} is tapped-load transformer impedance plus impedance of the conductors from the tap point to tapped-load transformer, and *m* is the per unit line impedance from the local relay to the tap point. Z_S is the local source impedance. V_L represents local bus voltage measurement, V_R represents remote line voltage measurement, and V_{TAP} represents voltage at the tap point. For now, we will focus on the required zone 2 reach to see various fault types on the low side of the tapped-load transformer.

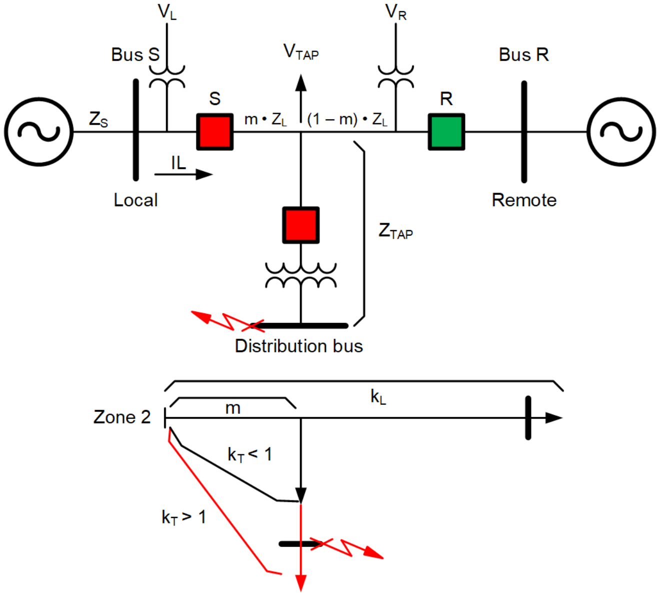

Fig. 2. Zone 2 reach with tapped load.

A. *Dyn Transformers—Apparent Reach for All Fault Types*

The most common winding configuration for tapped-load transformers is delta-connected windings on the line side, and wye-grounded windings on load side. This connection provides electrical isolation between the zero-sequence networks of the transmission lines and tapped load. Therefore, phase-to-ground distance elements (21G) cannot reach through a delta-wye transformer because of the absence of zero-sequence currents for low-side faults. This means only the zone 2 phase distance elements (21P) can operate for low-side faults because the 21P element will be permitted to operate for low-side faults within its reach. The 21P line distance relays will see an impedance of $m \bullet Z_L + Z_{TAP}$ for three-phase (3P) faults on the low-side distribution bus. However, for unbalanced faults the 21P will see an apparent impedance greater than $m \bullet Z_L + Z_{TAP}$.

Table I shows the required reach for a positive-sequence memory-polarized distance element to operate for a low-side fault on the distribution bus (as shown in Fig. 2) assuming an infinite source ($Z_S = 0$) with no remote infeed. The positive- and zero-sequence impedance of the tapped transformer are assumed to be equal.

TABLE I
21P ZONE 2 REACH TO OPERATE FOR LOW-SIDE FAULTS $Z_S = 0$ (DYN)

Fault Type	**Minimum Reach**	**Maximum Reach**
Three-phase (3P)	$1 \bullet (m \bullet Z_L + Z_{TAP})$	$1 \bullet (m \bullet Z_L + Z_{TAP})$
Phase-to-phase-to ground (PPG*)	$m \bullet Z_L + 1.05 \bullet Z_{TAP}$	$m \bullet Z_L + 1.2 \bullet Z_{TAP}$
Phase-to-phase (PP)	$1.05 \bullet (m \bullet Z_L + Z_{TAP})$	$1.33 \bullet (m \bullet Z_L + Z_{TAP})$
Phase-to-ground (PG)	$m \bullet Z_L + 1.5 \bullet Z_{TAP}$	$m \bullet Z_L + 1.5 \bullet Z_{TAP}$

*as m increases, the 1.05 and 1.2 factors slightly increase.

The Maximum Reach column is under no-load conditions and assumes the maximum torque angle (MTA) setting of the distance element is set at 90 degrees. This will closely match the mainly inductive nature of the transformer.

The Minimum Reach column is under transformer full-load conditions and the MTA of the distance element is set at 70 degrees. The 21 elements will be set in terms of the line characteristic impedance angle to provide the best performance for line faults, and in some systems, this can be as low as 70 degrees.

3P faults pose the highest risk of overreach because a distance element will correctly measure $m \bullet Z_L + Z_{TAP}$ apparent impedance value. Under heavy tapped-load conditions, low-side PP and PPG faults can pose nearly the same risk of overreach as 3P faults. PG faults will have a relatively high apparent impedance relative to a 3P fault.

The reach for 21P to operate for a low-side fault on a Ydn transformer will be similar to a Dyn transformer for 3P and PP faults. Because of the absence of a ground path on the low side, the required 21P reach to see PPG faults will be the same as a Dyn PP fault. 21P will not operate for low-side PG faults for a Ydn transformer in a low-side ungrounded system.

Appendix A provides a more in-depth analysis on the reach required by the line distance relays to operate for various low-side faults and illustrates the effects of source impedance, line angle, and loading of the tapped transformer.

B. *Zone 2 Step Distance Reach Considerations (Low-Side 3P Faults)*

Equation (1) defines the requirement to maintain security for low-side faults and dependability for line faults. k_L (in per unit) is the minimum zone 2 reach needed for dependability, and k_T (in per unit) is the maximum zone 2 reach allowed for security. This equation is valid for low-side 3P faults, which present the worst case for phase distance element overreach.

$$k_{T(3P)} \bullet (m \bullet Z_L + Z_{TAP}) \le Z_L \bullet k_L \tag{1}$$

We can rearrange (1) to find ($k_{T[3P]}$) for a given system (2). In most applications, the minimum k_L needed for dependability for line faults is 1.2 and the maximum $k_{T(3P)}$ allowable for security for low-side transformer faults is 0.8.

$$k_{T(3P)} \le \frac{k_L}{m + \dfrac{Z_{TAP}}{Z_L}} \tag{2}$$

For example, if $k_L = 1.2$, $m = 0.5$ and $Z_{TAP} = Z_L$, then $k_{T(3P)}$ would evaluate to 0.8, and zone 2 would provide adequate dependability for line faults and remain secure for faults on the low side of the tapped-load transformer. However, if the tapped load was at $m = 0.2$, $k_{T(3P)}$ evaluates to 1, meaning that zone 2 will have to reach through the transformer for low-side 3P faults to maintain dependability for all line faults. Alternatively, the zone 2 reach can be set to satisfy $k_{T(3P)} < 0.8$, and a phase time-overcurrent element can be used to detect line-end faults and coordinate with tapped-load faults.

C. *Zone 2 Pilot Considerations (Low-Side 3P Faults)*

Transient overreach is a short duration of time at the initiation of a fault in which a distance element may reach beyond the set point before settling into the steady-state fault condition. A traditional zone 1 element, which is set as an underreaching instantaneous zone of protection, often includes additional supervision to mitigate transient overreach to maintain element security. In some cases, the maximum transient overreach of a distance element is only specified for zone 1.

Traditional zone 2 elements are set to overreach the remote bus for dependability and may not have the additional supervision to mitigate transient overreach security concerns. This is an important consideration in tapped-load applications because a zone 2 element that operates instantaneously in conjunction with a pilot scheme must remain secure for faults on the low side of the tapped-load transformer. In effect, zone 2 is now an underreaching zone in regards to the tapped-load faults.

If the zone 2 elements used in a pilot scheme do not have a published maximum transient overreach comparable to a zone 1 element, then consider adding a short time delay to the zone 2 element (i.e., 2 cycles) to ride through the transient overreach portion of the event. This will allow you to keep a $k_{T(3P)}$ factor equivalent to what you use for step distance protection.

D. Zone 1 Reach Considerations (Low-Side 3P Faults)

While (1) and (2) define the reach limitations for a zone 2 element for line fault dependability and low-side fault security, the zone 1 element has different considerations. The zone 1 element must not overreach the distribution bus, nor the remote line terminal. As such, the allowable zone 1 reach is defined by (3) without infeed.

$$Z1_{REACH} = \min\left[0.8 \cdot (m \cdot Z_L + Z_{TAP}), 0.8 \cdot Z_L\right] \qquad (3)$$

E. Autotransformer—Apparent Reach for All Fault Types

With the removal of the tapped transformer phase shift, the 21P distance elements will now measure $m \cdot Z_L + Z_{TAP}$ apparent impedance value for low-side 3P, PP, and PPG faults regardless of source impedance.

For this tapped transformer configuration, the 21G elements in the transmission line relay will be permitted to operate because the zero-sequence network is electrically connected between the transmission line and the tapped load.

The zero-sequence compensation factor (k0) used to develop the operating current for ground distance elements is a function of the positive- and zero-sequence impedance line parameters. In general, the zero-sequence impedance of a line is around three times the positive-sequence impedance. In transformers, the zero-sequence and positive-sequence impedance may be nearly equal. This large discrepancy can lead to 21G overreach, especially if the transformer is tapped close to the relay location.

However, autotransformers have a shunt connection in the zero-sequence network due to the tertiary winding, which will divert some zero-sequence current from the relay location. This tends to make distance elements underreach for low-side PG faults.

In general, low-side PG faults on autotransformers should be carefully analyzed to ensure the ground distance element will not operate for low-side PG faults. The general guidance of setting the reach with $k_{T(3P)} = 0.8$ may not provide enough security in some systems.

IV. HYBRID PERMISSIVE OVERREACHING TRANSFER TRIP

Without a tapped-load blocking signal, DCB pilot schemes are not secure when one or both line terminals' zone 2 distance elements overreach the tapped-load transformer. However, if only one terminal's zone 2 overreaches the low-side distribution bus to provide adequate dependability for line faults, a permissive overreaching transfer trip (POTT) scheme remains secure even without a blocking signal from the tapped-load station. For a low-side fault, the zone 2 in the local terminal will operate, but the local terminal will not receive a permissive signal from the remote terminal because it does not see this fault. However, a hybrid POTT scheme, which includes echo logic, will *not* be secure in this case. Hybrid POTT is no different from DCB in this regard. When the zone 2 in the local terminal operates, it sends permission to the remote terminal; the remote terminal will echo the permission back to the local terminal because the remote terminal does not see a fault. One option to maintain security is to disable echo logic in the hybrid POTT scheme.

One disadvantage of using a POTT scheme with echo logic disabled is that EOL faults will not be cleared instantaneously with RTO. To provide fast fault clearing for EOL faults, echo logic needs to be enabled when using a POTT scheme. To prevent echo logic security issues for low-side faults, voltage supervision (VSUP) can be added to the voltage echo logic (V_{ECHO}).

Fig. 3 provides a simple example of why adding VSUP to the echo logic works in this application. Fig. 3 shows the voltage profile for faults that occur on the line and the low-side distribution bus in Fig. 2.

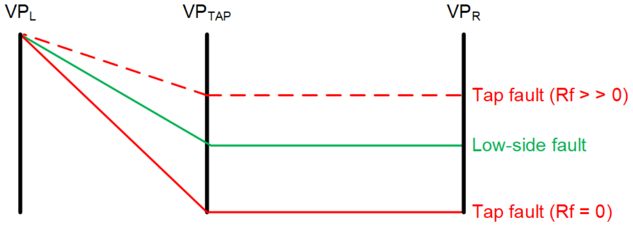

Fig. 3. Phase voltage profile for 3P faults with RTO ($Z_S = 0$).

When a low-side 3P fault occurs, $VP_R = VP_{TAP}$ (where VP is the minimum of VA, VB, or VC). In many cases, this voltage will be relatively high, as represented by the green line in Fig. 3, because a significant portion of the voltage drop to the fault occurs across the transformer impedance.

If a bolted 3P fault occurs anywhere on the line, VP_R will be zero. The solid red line in Fig. 3 represents a bolted 3P line fault at the tap point. The large difference between VP_R for 3P faults on the low side of the transformer compared to 3P faults on the line can be used to determine the location of the fault and either restrain (VP_R is high) or permit (VP_R is low) the 21 elements at Terminal S to operate.

However, using VSUP at Terminal R can reduce the fault resistance (Rf) coverage for the 21 elements at Terminal S. The dotted red line shows a 3P fault on the line at the tap point with Rf that produces a relatively high voltage at VP_R. While high Rf can reduce sensitivity of the pilot scheme, the addition of VSUP to the echo logic at Terminal R still provides fast fault clearing from Terminal S for line faults with low Rf when the Terminal R is open or weak.

A. Hybrid POTT Logic With VSUP

Hybrid POTT logic includes echo logic, which gives a hybrid POTT scheme parity with a DCB scheme. In this section, we focus on the echo logic portion of the hybrid POTT logic.

In scenarios when one of the terminals in a two-terminal line is unable to key permission for an internal fault, the echo logic provides improved dependability. At minimum, the echo logic will echo the received permission back if no reverse fault is detected, permitting a remote terminal operation. By this simple definition of echo logic, a hybrid POTT scheme with a properly functioning communications channel will have the same sensitivity for high-resistance faults as a DCB scheme.

The echo logic is often synonymous with weak infeed logic in the relays that offer hybrid POTT schemes. While echo logic does provide dependability improvements when one terminal is weak, the echo logic can provide sensitivity improvements, regardless of terminal strength [3]. For example, if a high-resistance fault occurs close-in to the local terminal, it will detect the fault and key permission to the remote terminal. The remote terminal may not have protection elements sensitive enough to detect this fault, even if the terminal is relatively strong. The lack of fault detection at the remote terminal can be used to echo the received permission back to the local terminal to clear the fault quickly. Again, this provides the same sensitivity as a DCB scheme.

To acknowledge the benefits of the echo logic in strong and weak systems, we remove the "weak infeed" moniker in the generalized three-pole echo logic in Fig. 4. We show VSUP settings to allow a user to provide their preferred security and sensitivity balance in systems with or without tapped loads on the line. The logic is split into two echo logic pieces: three-pole open echo logic (3PO_ECHO) and three-pole closed echo logic (3PC_ECHO). The difference is that 3PC_ECHO (often referred to as weak infeed echo logic) must determine that no forward fault or reverse fault has been detected, whereas3PO_ECHO (often referred to as open-breaker echo logic) does not have this requirement.

We include an option for weak infeed tripping (WI_TRIP) for the 3PC_ECHO logic. While 3PC_ECHO does not require VSUP in many applications, tripping the local terminal does require VSUP, even if no fault is detected using current-based elements. Under a system contingency when the terminal becomes weak, the voltage-supervised WI_TRIP can trip the terminal to provide dependability.

We also include an option for keying on 3PO (3PO_KEY) with optional VSUP, which can be useful in tapped-load applications where only one communications bit is available. Again, this overall logic is generalized, but many relays in service today can be modified to operate similarly to Fig. 4 with custom relay logic.

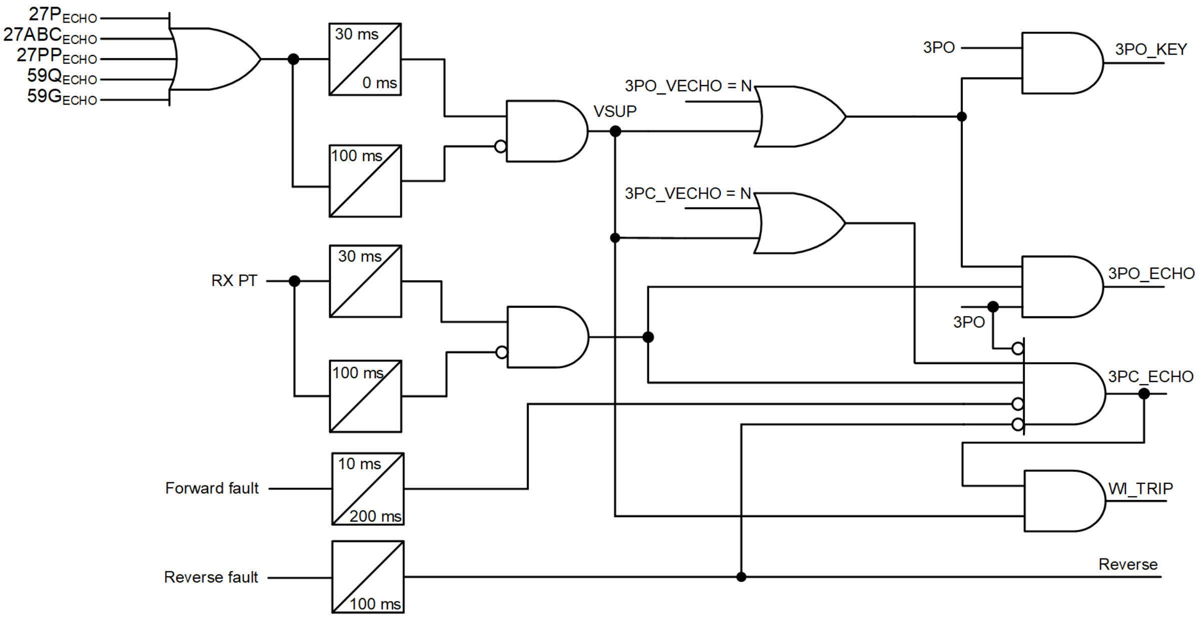

Fig. 4. Open breaker key and open and close breaker echo logic with optional VSUP.

1) *Three-Pole Closed-Breaker Echo (3PC_ECHO)*

The received permission to trip (RX PT) can be thought of as an “echo request” [4]. The request is qualified with a short pickup timer to guard against noise bursts on the communications channel. The duration of the echo, if permitted, is limited to prevent channel lockup. With the breaker closed, we need to guard against current reversal and check for reverse faults. The following must occur for the echo request to be permitted:

- No reverse fault or forward fault has recently occurred. This provides security for external faults, even during current reversals.
- The breaker is closed.
- VSUP (optional).

VSUP can serve multiple purposes. The optional VSUP is used for a closed breaker when 3PC_VECHO = Y:

- In lines with no tapped loads, ensuring an abnormal voltage is present provides an additional level of security, especially in cases in which dependability biased directional elements [5] in the remote relay can operate for non-fault conditions.
- In tapped-load applications, VSUP can be used to restrain the remote relay for faults on the low side of a tapped transformer.

For users that prefer maximum sensitivity on lines with untapped loads and/or have reasonably balanced the security and dependability of local and remote directional elements, VSUP may be disabled. However, on lines with tapped loads in which distance elements can operate for low-side faults, VSUP should be enabled. Appendix B discusses the sensitivity reduction in using VSUP with echo logic.

2) *Weak Infeed Trip (WI_TRIP)*

A 3PC_ECHO is granted if the following conditions are met: the local breaker is closed, the local relay receives permission to trip (PT) from the remote terminal, and it detects no fault (forward or reverse). If there is an abnormal voltage condition present at that time, then this indicates that the fault is on the line and WI_TRIP is permitted to open the local terminal. This essentially confirms the remote detection of the fault from the strong terminal with a local measurement that there is a fault (low or unbalanced voltage) before tripping the local breaker. Note that this will only operate for a weak source, so using the term “weak infeed trip” is appropriate here.

3) *Three-Pole Open-Breaker Echo (3PO_ECHO)*

With the breaker open, we do not need to guard against current reversal, nor check to ensure a reverse fault has occurred. In most applications, additional VSUP is not needed (3PO_VECHO = N). However, in lines with tapped loads, VSUP may still be needed to prevent remote relay distance elements for tripping for low-side tapped-load faults (3PO_VECHO = Y) by taking advantage of the voltage profile characteristics illustrated in Fig. 3.

4) *Three-Pole Open Breaker Key (3PO_KEY)*

The open breaker keying can be used in channels where channel lockup is not expected. Instead of receiving an echo request from the remote terminal, the local terminal with the open breaker keys permissive to trip to the remote terminal, allowing the remote terminal to operate on its protection elements. In this logic we add the ability to supervise open breaker keying with voltage for lines with tapped loads. In Section V, we will detail cases in which this can be a useful alternative to 3PO_ECHO.

5) *VSUP and Time Window*

In Fig. 4, the voltage elements have two timers to provide security under transient conditions: loss of potential (LOP) conditions and preventing channel lockup. The 30 ms pickup timer is to ensure the condition has existed for a long enough time to consider it a valid condition to grant an echo request via VSUP. However, if this condition exists for over 100 ms, the VSUP is shut down to guard against cases in which an LOP condition has occurred to prevent security issues and channel lockup. Because this VSUP can be used in open- and closed-pole configurations, relying on traditional LOP, which also relies on current, is not viable. Normally applied voltages immediately allow the VSUP to re-enable.

The following are the descriptions for each voltage element word bit as well as the line fault types, for which they provide dependability. The following discussion is in the context of using these elements to provide dependability for line faults while providing security for 21 elements with tapped loads:

- $27P_{ECHO}$—asserts when the minimum PG voltage is lower than the threshold setting. Provides dependability for all line fault types except PP. $27P_{ECHO}$ can primarily be used with autotransformers as tapped loads, but it can also be used in place of $27ABC_{ECHO}$ with Dyn transformers.
- $27ABC_{ECHO}$—asserts when all three PG voltages are lower than the threshold setting. Provides dependability for 3P line faults.
- $27PP_{ECHO}$—asserts when the minimum PP voltage is lower than the threshold setting. Provides dependability for 3P, PP, and PPG fault types, especially in weak systems.
- $59Q_{ECHO}$—asserts when the negative-sequence voltage is higher than the threshold setting. Provides dependability for unbalanced line faults in relatively strong systems.
- $59G_{ECHO}$—asserts when the zero-sequence voltage is higher than the threshold setting. Provides dependability for ground faults on the line and can be set very sensitive in Dyn applications.

B. *Requirements for V_{ECHO}*

The use of VSUP in the echo logic requires 3P line-side wye-connected voltage transformers (VTs) to make 21P and 21G dependable for a line fault while ensuring security for all low-side faults. At subtransmission voltage levels in which a single-bus single-breaker bus arrangement is common, only a single line VT may be available, typically for synchronization. Using this scheme will require the addition of two VTs, and the line relaying functions from the bus VTs will need to be moved to the line VTs. This may be unappealing, but in some cases it may be less problematic than adding block signals at tapped-load locations, especially if the tapped loads are not owned by the utility.

C. V_{ECHO} Setting Guidance—Dyn Transformers

To use this voltage-supervised echo logic, the lowest phase voltage available at remote relay VP_R for a low-side distribution bus 3P fault must be found. The voltage can be found by determining a reasonable system contingency when Z_S is largest (weakest source), opening the remote line terminal breaker, and placing a 3P fault on the low-side distribution bus. The line-to-neutral voltage at the remote terminal under these conditions ($VP_{R[3P]}$) is multiplied by a security factor of 0.8 and becomes the setting for $27ABC_{ECHO}$ (4).

$$27ABC_{echo} = 0.8 \bullet VP_{R(3P)} \tag{4}$$

Other fault types on the low-side distribution bus (PP, PPG, and PG), will all produce a voltage equal to or greater than $VP_{R(3P)}$. This means the setting provides security for all fault types on the low side of a Dyn or Ydn transformer. If the remote voltage VP_R is less than 0.2 • VNOM (L-N) for the low-side distribution bus 3P fault, then the VSUP cannot be applied securely to the echo logic. This can occur in very weak systems. Under these conditions, the voltage developed for a low-side 3P fault is too low to distinguish between a low-side distribution bus 3P fault and line 3P fault reliably.

While $27ABC_{ECHO}$ provides security for all low-side faults, it will prevent operation of zone 2 distance elements for unbalanced faults on the line. Therefore, $27P_{ECHO}$, $27PP_{ECHO}$, $59Q_{ECHO}$, and $59G_{ECHO}$ voltage elements are also used to provide dependability for unbalanced line faults. To use these elements securely, the worst-case value for low-side faults of VPP_R (PP), VQ_R (negative-sequence), and VG_R (zero-sequence) must be found. The lowest VPP_R is simply $VP_{R(3P)}$ multiplied by √3.

$59G_{ECHO}$ can be set at 0.15 • VNOM (L-N) because VG_R will be zero for low-side distribution bus faults for a Dyn or Ydn transformer. This allows for up to a 15 percent zero-sequence voltage to be present during low-side faults and still maintain security.

$59Q_{ECHO}$ can be set quite low as well, but the setting does depend on how much zone 2 overreaches the tapped load. Appendix E shows that if the zone 2 reach is set to be secure for low-side distribution bus PG faults, then a setting of 0.2 • VNOM (L-N) will provide security for low-side PP and PPG distribution bus faults. Note that (5), which details zone 2 boundary conditions for low-side distribution bus PG faults, is very similar to (2), which details zone 2 boundary conditions for low-side distribution bus 3P faults.

$$k_{T(PG)} \le \frac{k_L}{m + 1.5 \bullet \dfrac{Z_{TAP}}{Z_L}} \tag{5}$$

If $k_{T(PG)}$ evaluates to more than 0.8, then find $VQ_{R(PP)}$, which is the negative-sequence voltage available at the remote relay for a low-side distribution bus PP fault for a reasonable system contingency case when Z_S is largest with RTO condition, and multiply it by a security factor of 1.25.

Table II shows the voltage setting recommendations for a Dyn-/Ydn-tapped load transformer applications.

TABLE II
V_{ECHO} SETTING RECOMMENDATIONS FOR DYN/YDN TRANSFORMER

Element Setting	Dyn/Ydn
$27ABC_{ECHO}$ $27P_{ECHO}$	0.8 • $VP_{R(3P)}$
$27PP_{ECHO}$	√3 • 0.8 • $VP_{R(3P)}$
$59G_{ECHO}$	0.15 • VNOM
$59Q_{ECHO}$	0.2 • VNOM when $k_{T(PG)} < 0.8$ 1.25 • $VQ_{R(PP)}$ when $k_{T(PG)} > 0.8$

Notes:

If $VP_{R(3P)}$ is less than 0.2 • VNOM, find an alternate method to provide security for low-side faults.

If $VQ_{R(PP)}$ evaluates to a V2 of 0.4 • VNOM or higher, then disable $59Q_{ECHO}$ and rely on $27PP_{ECHO}$ to clear PP faults.

D. V_{ECHO} Setting Guidance—Autotransformers

For autotransformers, settings considerations for $27P_{ECHO}$, $59Q_{ECHO}$, and $59G_{ECHO}$ are different. Depending on various factors, the lowest value for VP_R may occur for a low-side PG or PPG fault rather than a 3P fault. Therefore, set $27P_{ECHO}$ based on the lowest PG voltage available. Set $59Q_{ECHO}$ based on the worst-case negative-sequence voltage available by checking all unbalanced fault types. Because a ground path exists between the relay location and a transformer low-side fault, a zero-sequence voltage will develop at V_R for low-side ground faults. This means that $59G_{ECHO}$ must be found by applying the PG and PPG fault on the low-side bus with the weakest source and remote end open.

Table III shows the settings recommendation summary for each voltage element for autotransformer tapped-load applications.

TABLE III
VOLTAGE ELEMENT SETTING RECOMMENDATIONS FOR AUTOTRANSFORMERS

Element Setting	Auto
$27ABC_{ECHO}$	0.8 • $VP_{R(3P)}$
$27PP_{ECHO}$	√3 • 0.8 • $VP_{R(3P)}$
$27P_{ECHO}$	0.8 • Min ($VP_{R[3P]}$,$VP_{R[PG]}$, $VP_{R[PPG]}$)
$59G_{ECHO}$	1.25 • Max ($VG_{R[PG]}$, $VG_{R[PPG]}$)
$59Q_{ECHO}$	1.25 • Max ($VQ_{R[PP],}$ $VQ_{R[PG]}$, $VQ_{R[PPG]}$)

Notes:

If $VP_{R(3P)}$ is less than 0.2 • VNOM, find an alternate method to provide security for low-side faults.

If $VQ_{R(PP)}$ evaluates to a V2 of 0.4 • VNOM or higher, then disable $59Q_{ECHO}$ and rely on $27PP_{ECHO}$ to clear PP faults.

In autotransformer applications, if $27P_{ECHO}$ evaluates to less than 0.2 • VNOM, find an alternate method to provide security for low-side faults.

E. Implementation

Fig. 5 shows how hybrid POTT schemes are commonly implemented, and how they only require one communications bit. Assertion of ECHO represents the assertion of 3PO_ECHO or 3PC_ECHO, as shown in Fig. 4. Reception of the PT with a local zone 2 assertion leads to a trip. The RX PT could be due to the assertion of remote zone 2 or echo logic. When using this logic, only one relay zone 2 can overreach the tapped load. The relay that does not overreach has V_{ECHO} enabled to only echo permission when the voltage indicates the fault is on the line.

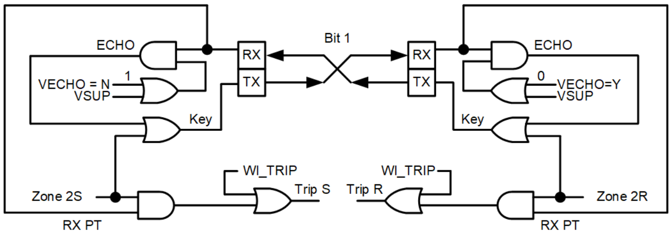

Fig. 5. POTT with VSUP to echo logic when Terminal S zone 2 overreaches a tapped load distribution bus.

In single or multiple tapped-load applications, the hybrid POTT scheme with voltage-supervised echo logic is reliable when both line breakers are closed, or the remote line breaker is open. When the line is sectionalized, the POTT scheme is effectively disabled.

V. Permissive Underreaching Transfer Trip

POTT pilot schemes are not secure when both line terminals' zone 2 overreach for low-side faults of the same tapped load. The permissive underreaching transfer trip (PUTT) scheme remains secure when both terminals zone 2 overreach a tapped load distribution bus because it uses zone 1 for permissive keying, which does not overreach a tapped load on the line. To ensure the PUTT scheme is dependable for line faults when both terminals are closed, the Z1 from each terminal must overlap zones of protection on the line. However, when the remote line terminal is open, the PUTT scheme does not provide instantaneous fault clearing for EOL faults. There are two ways to address this shortcoming.

The first option is adding a second communications bit and enabling VSUP for open- (3PO_VECHO = Y) and closed-breaker echo (3PC_VECHO = Y) logic from the POTT logic at both line relays. Fig. 6 shows a PUTT scheme to clear faults when both line terminals are closed, and with V_{ECHO} logic to clear faults when a remote line terminal is open. In the scenario in which each terminal asserts zone 2 elements, reception of a remote zone 1 PT element means the fault is on the line and the local relay is allowed to trip. However, if each relay asserts zone 2 elements and receives zone 2 PT, the fault may be on the low side of the transformer. Therefore, reception from a remote zone 2 PT does not allow a local trip. Instead, the zone 2 PT solely becomes an echo request, which is supervised by voltage to ensure the fault is on the line and not the low side of the transformer. If the EKEY request is granted, then the fault is on the line. The EKEY bit is transmitted back to the terminal requesting the echo on the same bit on which the zone 1 key is transmitted. If either a zone 1 PT is received or a zone 2 voltage-supervised EKEY is received, then local tripping is permitted. This provides 100 percent line coverage when both line terminals are closed (or any remote line terminal is open) when each terminal overreaches a tapped load distribution bus, even in weak infeed conditions.

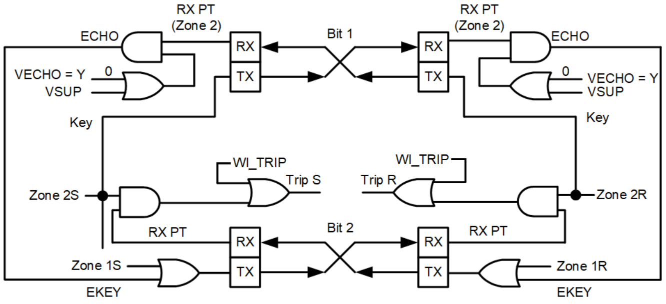

Fig. 6. PUTT with V_{ECHO} logic when both line terminals' overreach zone 2 overreaches a tapped load distribution bus.

The second option is using voltage-supervised 3PO_KEY (3PO_VECHO = Y) with the PUTT scheme channel (see Fig. 7).This option only requires one communications bit for the overall scheme. Fig. 7 shows a PUTT scheme with 3PO_KEY. In tapped-load applications, 3PO_KEY is voltage-supervised at remote terminals when the local terminal zone 2 overreaches the tapped load. When both line terminals are closed, the PUTT scheme provides 100 percent line coverage. When the remote line terminal is open, voltage-supervised 3PO_KEY provides 100 percent line coverage while providing security for low-side tapped-load faults. The logic in Fig. 7 is less complex than Fig. 6. However, Fig. 6 logic provides 100 percent line coverage in a weak infeed condition.

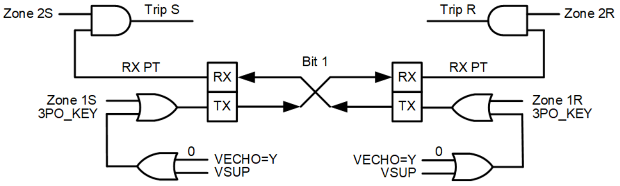

Fig. 7. PUTT with 3PO_KEY when both line terminals' zone 2 overreaches a tapped load distribution bus.

Like the POTT scheme, when the line is sectionalized, the PUTT scheme is also disabled.

VI. Application Considerations

In this section, we discuss multiple line taps to ensure the proper pilot scheme is selected for the application. Fig. 8 shows a two-terminal line with (*N*) tapped loads along the line. Each tapped load must be checked to see if either or both relays at Terminal S and Terminal R have adequate margin to prevent overreach.

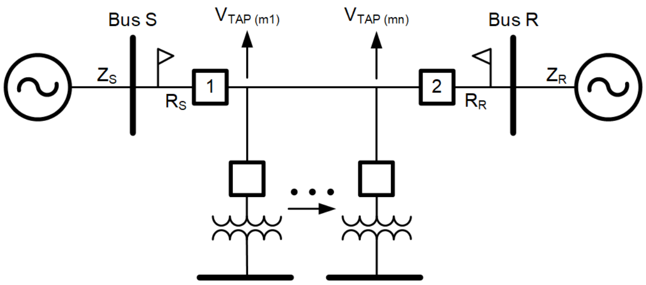

Fig. 8. Number *N* taps of two-terminal line.

A. *Pilot Scheme Selection Based on Reach*

$$k_{T(3P)(N)S} = \frac{k_L}{m_N + \dfrac{Z_{TAP(N)}}{Z_L}} \tag{6}$$

$$k_{T(3P)(N)R} = \frac{k_L}{(1 - m_N) + \dfrac{Z_{TAP(N)}}{Z_L}} \tag{7}$$

Follow these guidelines based on the results of (6) and (7).

After selecting the appropriate pilot scheme, use the guidance provided in the Sections IV.C and IV.D on setting the voltage elements if required to add VSUP to the echo logic for the permissive tripping schemes.

TABLE IV
PILOT SCHEME SELECTION

k_T	Pilot Scheme Preferred	Overreaching Terminal for Low-Side Faults	Remote Terminal Open Reliability
Both $k_{T(3P)(N)S}$ and $k_{T(3p)(N)R}$ are < 0.8	DCB	None	No extra logic needed.
$k_{T(3P)(N)S} > 0.8$, but $k_{T(3P)(N)R} < 0.8$	POTT (1)	Terminal S only	Enable echo without VSUP at Terminal S. Enable echo with VSUP at Terminal R.
$k_{T(3P)(N)S} < 0.8$, but $k_{T(3P)(N)R} > 0.8$	POTT*	Terminal R only	Enable echo with VSUP at Terminal S. Enable echo without VSUP at Terminal R.
Both $k_{T(3P)(N)S}$ and $k_{T(3p)(N)R}$ are > 0.8	PUTT*†	Both terminals	See Section V for the two options discussed.

*POTT/PUTT schemes lose dependability when the lines with tapped loads are sectionalized and a section of the line still in service falls outside zone 1 reach. The backup stepped distance element's zone 2 (Z2T) operates when the lines are sectionalized for faults outside zone 1. The restoration logic discussed in Section VII can be used to maintain the transmission tripping times.

†Refer to Section III.C for additional considerations for pilot scheme time.

It is possible to require VSUP to be enabled at Terminal S and Terminal R in a POTT scheme for multiple tapped loads on the line. For example, if $k_{T(3P)(1)S} > 0.8$ and $k_{T(3P)(1)R} < 0.8$, then Terminal S overreaches the first tapped load, and VSUP must be enabled at Terminal R and set based on a low-side fault at tapped load 1. If $k_{T(3P)(2)S} < 0.8$ and $k_{T(3P)(2)R} > 0.8$, then Terminal R overreaches the second tapped load, and VSUP must be enabled at Terminal S and set based on the low-side fault at tapped load 2. A PUTT scheme is only required when Terminal S and Terminal R overreach the same tapped load. In this case, enable VSUP at Terminal S and Terminal R and set based on the low-side fault at the tapped load both terminals overreach.

B. *Switch Onto Fault Considerations*

With the addition of VSUP to the echo logic (V_{ECHO}), the relays will only trip for line faults, therefore traditional distance elements with no time delay can be used for switch onto fault (SOTF), along with other protection elements conventionally used in a SOTF trip. This provides fast full-line clearing for permanent faults on the line during a reclose. Note that the V_{ECHO} logic will not permit an echo when reclosing into a permanent fault on the line. This is because the voltage will collapse on the initial fault, and the V_{ECHO} window will expire before the reclose occurs. In the application of transmission lines with a tapped load, consider the following options to keep distance elements used in SOTF secure for tapped transformer inrush conditions [6]:

- Supervise distance elements with undervoltage elements.
- Apply second-harmonic blocking.
- Set overcurrent fault detectors higher than maximum inrush current.

VII. RESTORATION LOGIC

In this section we discuss restoration logic in the transmission line relays and low-side relays. Implementing custom restoration logic when the transmission line relay stepped distance scheme overreaches the tapped load low-side distribution bus helps restore the transmission line into service after a low-side fault has occurred.

The restoration logic is useful only if the stepped distance scheme is miscoordinated for low-side faults. In this section, we have assumed that the zone 2 used in the pilot scheme is also used in the stepped distance scheme. However, it is not necessary to use the distance elements with same reach in each scheme. The restoration logic is only used if a low-side fault is cleared slower than the zone 2 time-delay (Z2D) timer. If the low-side protection trips faster than Z2D, then the transmission relay does not trip and restoration logic is not activated because it is not needed.

The general idea of the restoration scheme is that Z2T in the transmission line relay will miscoordinate for permanent low-side faults for the first trip. After the first trip, the transmission line relay coordinates with the low-side protective devices.

A. *Sequence of Events*

1) *Low-Side Fault Clearing*

- If the low-side protective device clears the fault in under the Z2D time-delay, then Z2T will not operate and the restoration logic is effectively bypassed.
- If the Z2T operates for the low-side fault and the line trips, then the low-side relay responsible for clearing faults downstream of the transformer detects the fault because of the pickup of time-overcurrent elements before the line trips. After the line trips, the low-side relay detects a loss of voltage in all three phases indicating the line tripped to clear the downstream fault. This prompts the low-side relay to initiate trip and enter reclosing mode.

- The transmission line relay closes its breaker before the downstream low-side breaker and enables SOTF elements. The SOTF elements are only enabled for a short duration to allow instantaneous element operation when the line is reclosing into a permanent line fault.

  The low-side relay is allowed to close its breaker only after the SOTF elements are no longer active in the transmission line relay. This is accomplished by coordinating the reclosing open interval of the low-side relay with the SOTF enable duration.
- After the low-side relay recloses, if the fault is permanent in nature, it trips again by its local protective elements. The Z2T element for the transmission line relay is prevented from operating after reclosing by blocking it while the reclosing state for the transmission line relay is active.
- Time-overcurrent elements in the transmission line relays provide backup in case the low-side relay is not able to clear the fault. They are set to coordinate with the low-side relay.

2) *Transmission Line Fault Clearing*

- Faults within zone 1 reach are cleared instantaneously by zone 1. Faults outside zone 1 reach are cleared by zone 2 in the Z2D in the event that the communications scheme is inactive. After the line recloses, if the fault is permanent, it trips instantaneously on the SOTF element.
- After the line breaker recloses without a line fault present, the breaker remains in a reclosing cycle state before transitioning to the reset state. If the line fault reappears after the SOTF enable duration is expired with the breaker in the reclosing state, the fault will be cleared by the time-overcurrent elements in the transmission line relay.

B. *Logic Implementation*

In this section we will discuss how to implement the restoration logic in the transmission line relay and the distribution feeder relays.

1) *Transmission Line Relay*

This logic needs to be implemented in the transmission line relay or relays in which zone 2 distance elements can overreach for low-side faults.

- Zone 1 is set according to equation (3).
- Zone 2 is set to cover 120 percent of line impedance with a time delay of 20 cycles or based on the utility standard for setting zone 2 reach and time delay.
- SOTF trip is enabled.
- The Z2T is armed to trip only if the breaker is in the reset state, as shown in Fig. 9.
- The time delay for transitioning from a reclosing cycle state to reclosing reset state should be equal to the low-side distribution feeder relays with the longest reclosing sequence time plus a safety margin.
- For remote terminal closed (RTC) conditions, when only one line terminal overreaches for low-side faults and trips for the low-side fault, the low-side bus voltages will not be dead because the other line terminal that does not overreach for low-side faults is still closed. In such cases, the reclosing open interval of the line terminal that overreaches needs to be longer than the low-side fault-clearing time. This allows the low-side relay to isolate the fault and prevent the line terminal from reclosing into the fault. A reclosing open interval of no less than two seconds is recommended in this application.

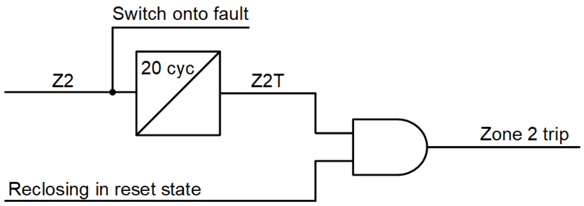

Fig. 9. Transmission line relay logic.

2) *Distribution Feeder Relay*

This logic (shown in Fig. 10) needs to be implemented in the low-side distribution feeder relays.

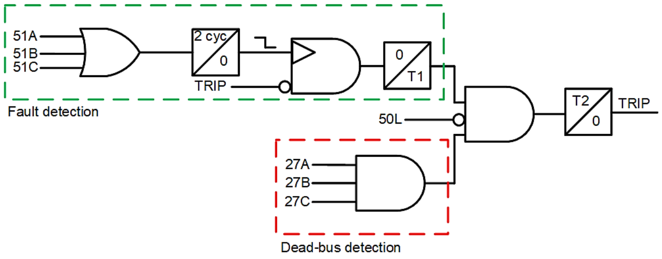

Fig. 10. Distribution feeder relay logic.

a) *Fault Detection*

The pickup of any time-overcurrent elements (51A, 51B, or 51C) is an indication of a downstream fault. The two-cycle pickup timer provides security against transient conditions. When the fault is cleared by the downstream relay or the upstream line relay Z2T, the low-side relay will see deassertion (falling edge) of the time-overcurrent element. This opens the window (dropout timer T1) to check for dead-bus voltage. The dropout timer T1 is set to 60 cycles.

b) *Dead-Bus Detection*

The tripping of the transmission line will cause the low-side 3P bus voltages to go to zero. Therefore, the pickup set point for the phase undervoltage element (27P) is set low, equal to 0.15 • VNOM with no intentional time delay.

c) *50L*

When there is a close-in 3P permanent fault cleared by a downstream recloser, the recloser will trip and initiate reclosing. This will make the fault detection logic in the distribution feeder true, and it will open the 60-cycle window to check for dead-bus voltage. Because the fault is downstream and isolated, the bus voltages will be healthy, and the restoration logic is blocked. If the downstream recloser recloses within 60 cycles, dead-bus logic can assert from the voltage depression from the nearby fault. The addition of 50L blocks the logic from operating as the downstream protective device recloses into the fault. The set point for 50L is 0.1 • INOM.

The security pickup timer T2 is set equal to 30 cycles. This assumes that the reclosing open interval timer in the transmission line relay is longer than 30 cycles.

d) Reclosing Considerations

For the restoration logic to work correctly, the transmission line breaker must close its breaker first after tripping for low-side faults, and the low-side relay must be allowed to close its breaker only when the SOTF enable duration in the transmission line relay has expired.

VIII. CONCLUSION

Transmission lines with tapped loads can create challenges for distance elements. In applications where the tapped loads are near one terminal on long lines, distance elements can overreach for low-side faults. For Dyn- and Ydn-tapped transformers, the worst fault type for zone 2 overreach is a 3P fault on the low-side distribution bus.

We also discuss application considerations with respect to pilot schemes in this paper:

- If one of the line terminals has a zone 2 element that overreaches for low-side faults, apply a DCB scheme, which naturally works well in a line that can be sectionalized.
- If one of the line terminals has a zone 2 element that overreaches for low-side faults, use a POTT scheme and add voltage supervision to echo logic at the line terminal that is not overreaching for low-side faults. The addition of voltage-supervision to the echo logic allows for high-speed clearing for the full line under remote terminal open conditions while remaining secure for low-side faults.
- If both the line terminals have a zone 2 element that overreaches for low-side faults, then apply a PUTT scheme. Either voltage-supervised echo logic or voltage-supervised open breaker keying can be used to provide high-speed clearing for the full line under remote terminal open conditions.

In the case that a stepped distance scheme overreaches a tapped-load distribution bus, the restoration logic will restore the transmission line back to service while allowing the low-side relays to isolate the fault.

IX. APPENDIX A

In this section, we will discuss the reach required in transmission line relay R1 for different faults on the low-side bus of the tapped transformer. We will explore how various factors, such as source impedance, line angle, and loading influence these values.

Fig. 11 shows our system example where we remove the infeed effect from the remote end of Bus R to consider the worst case. The infeed effect from the remote end will increase the reach required to operate for the low-side faults. In this scenario:

- $Z_{TAP} = Z_L = 1$ pu.
- $m \cdot Z_L = 0$ (this represents the worst case, because $m \cdot Z_L > 0$ would increase the reach required to operate for the low-side faults).
- Zone 2 is set equal to 1.2 pu in relay R1.
- The tapped transformer is Dy1.
- The expected reach required to operate for the low-side bus fault is Z_{TAP} (i.e., 1 pu).

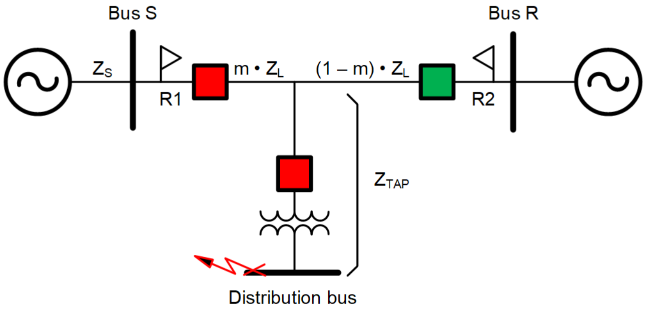

Fig. 11. Example system.

A. Single-Phase-to-Ground (AG Fault)

The reach required to operate for the low-side bus PG fault is $1.5 \cdot Z_{TAP}$ pu (i.e., 1.5 pu). Appendix D provides the mathematical derivation for the same. This occurs because of the phase shift introduced by the Dyn transformer [7]. The ground distance elements will not operate because of the absence of I0 currents.

The source impedance does not affect the reach required (i.e., 1.5 pu) for low-side bus PG faults, as seen in Fig. 12. The other phase fault loops, ZAB and ZBC, are not shown because they are nowhere near the operating region.

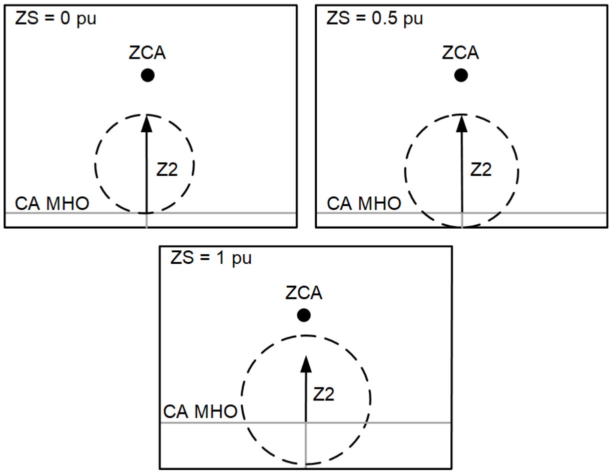

Fig. 12. Effect of source impedance on phase fault loop for low-side bus AG fault (no-load conditions).

The mho characteristics will tilt according to the line angle. For low-side bus PG faults, there is a security margin of 20 percent when the line angle is 90 degrees. For lower line angle values, the security margin will increase even further, so the line angle value is not a concern for the low-side bus PG fault.

In the previous scenario, we did not consider the loading of the tapped transformer. The transformer may possess varying MVA ratings for different cooling classes, with the maximum MVA rating being 1.67 times the base MVA rating. As the load increases, the reach required for the ZCA fault loop to operate is still 1.5 • Z_{TAP}, but it moves slightly to the right because of the load, as shown in Fig. 13. The source impedance considered in this case is 0 pu.

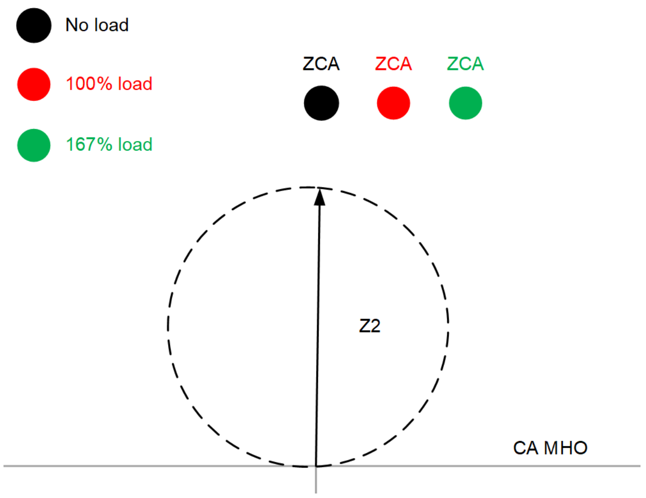

Fig. 13. Effect of loading of tapped load on phase fault loop for low-side bus AG fault.

In conclusion, the reach required to operate for PG faults on the low-side bus is equal to 1.5 • Z_{TAP} (i.e., 1.5 pu). This considers the worst-case scenarios of source impedance, line angle, and load. Therefore, the zone 2 reach settings of 1.2 pu are both dependable and secure for this type of fault.

B. *Phase-to-Phase (BC Fault)*

For BC faults on the line, we expect the BC phase fault loop to operate; however, for BC phase faults on the low-side bus, we see in Fig. 14 that the BC and AB phase fault loops can operate. The CA fault loop is nowhere near the operating region.

The source impedance affects the reach required to operate for low-side PP faults. In lower source impedance systems, the reach required to operate for a low-side PP fault will be relatively lower as compared to a higher source impedance system, making it more likely to enter the operating region of zone 2. Appendix C provides the mathematical calculation for the same. In Fig. 14, we assumed the source impedance ZS = 0 pu, which is the worst case. Fig. 14 shows that the low line angle tilts the mho characteristics of zone 2 such that phase fault loop AB enters the operating region even at no-load conditions for line angle 70 degrees. As the loading increases, the fault loop ZAB approaches the operating region, whereas the fault loop ZBC recedes from it. At transformer maximum loading (transformer with 12 percent impedance considered), the fault loop ZAB enters the operating region even when the line angle is 90 degrees. In summary, low source impedance, lower line angle, and/or loading of the tapped transformer increases the likelihood of phase distance elements tripping for low-side PP faults.

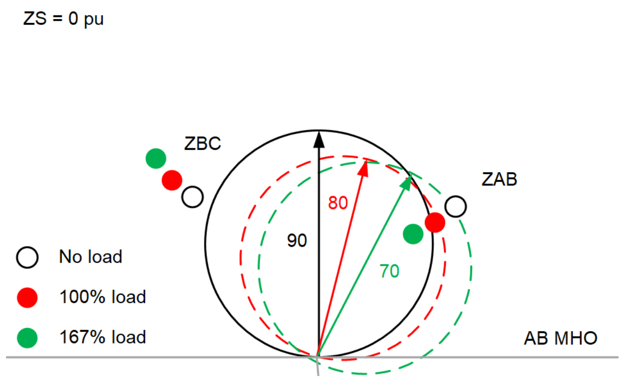

Fig. 14. Phase fault loop for low-side bus BC fault.

C. *Phase-to-Phase-to-Ground (BCG Fault)*

Like a low-side PP fault, the ZAB and ZBC fault loops can operate for a PPG fault on the low-side bus. ZBC is not shown in Fig. 15 for simplicity. However, as shown in Fig. 15, a distinguishing feature of the PPG fault is that the angle of these phase fault loops aligns more closely with typical line angle settings compared to that of a low-side PP fault. This means only lower source impedance and more load affects the likelihood of phase distance elements to operate for low-side PPG faults.

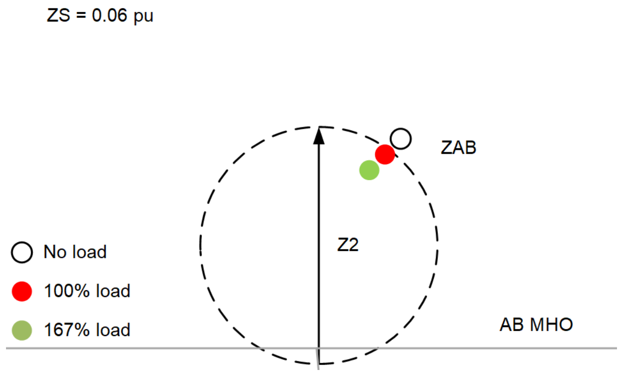

Fig. 15. Phase fault loop for low-side bus BCG fault.

D. *3P Faults*

The reach required to operate for the 3P fault on the low side bus will always be Z_{TAP} (i.e., 1 pu from the local relay). The source impedance, the line angle, and the loading have no effect on its value. As mentioned earlier, the bolted 3P faults on the line will have 0 volts, and the bolted 3P faults on the low-side bus will have more than 0 volts because of voltage drop across the tapped transformer impedance, and this basic distinction can be used to set the 27 elements to add VSUP to echo logic to secure the distance elements.

E. *Effect of V1 Memory Voltage*

Another factor that could affect the distance element security is the effect of V1 memory voltage. Because of various contributing factors, the V1 memory voltage is used as a polarizing quantity in distance elements [8].

As shown in Fig. 16, during the initial state of the fault, the relay will have 100 percent memory voltage available (i.e., the mho characteristics expand depending on the source impedance). A larger source impedance results in more expansion. For that instant, the zone 2 will not operate for the low-side bus PPG fault. As time goes by, the mho characteristic starts to shrink, i.e., the memory component in the V1 memory voltage starts reducing. When the memory component in the V1 memory voltage completely expires, the zone 2 operating region encompasses the AB fault loop impedance.

The duration for which the memory component is used is limited for various reasons [8]. Therefore, depending on the fault-clearing time, it is possible that the low-side fault is present and the memory component of the V1 memory voltage has completely expired, which can lead to zone 2 misoperation for the low-side bus PPG fault. If the security margin between the zone 2 reach and the reach required to operate for the low-side bus PP and PG faults is small, then we will see the same effect of V1 memory voltage leading to misoperation when the memory voltage expires. This is not a concern when VSUP (V_{ECHO}) is added to the echo logic because it will prevent the operation of distance for low-side faults regardless of the state of the V1 memory voltage.

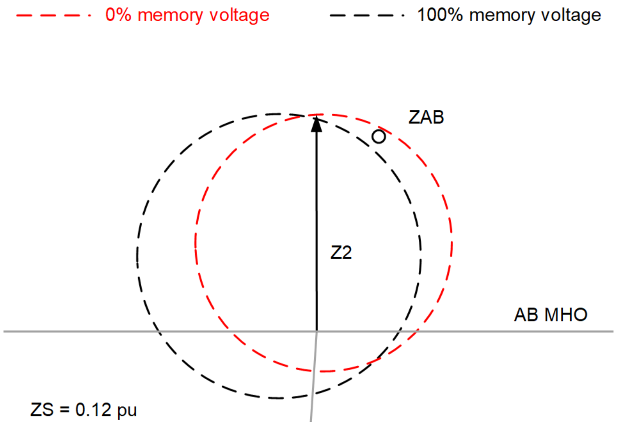

Fig. 16. Effect of memory voltage on zone 2 for low-side bus BCG fault.

X. APPENDIX B

Appendix B discusses the sensitivity of the distance elements by adding the remote VSUP to the echo logic and its effect on the load.

A. Sensitivity

In this section, we show the effective characteristic of supervising the local distance elements with remote voltage. We use the guidance provided in [9] to plot voltage elements in the impedance plane, keeping in mind that the effective location of the relay is at the fault location when voltage is measured at the end of the line with the breaker open. We plot the voltage characteristic at m = 0 and m = 1, and we use a line to connect the maximum R coverage from m = 0 and m = 1. The resultant characteristic is shown in Fig. 17 and Fig. 18 as a dashed line.

For ground faults on the low side, 21G will not operate because of a lack of I0 currents, but for ground faults on the line (i.e., PG and PPG) with Dyn-tapped transformers, dependability of 21G will be provided by $59G_{ECHO}$. The sensitivity limitation is not a concern because $59G_{ECHO}$ is set very low and no zero-sequence voltage will develop for any low-side fault. In autotransformer-tapped load applications, $59G_{ECHO}$ can inhibit PG and PPG Rf coverage because V0 will develop for these low-side fault types.

For Dyn-tapped load transformers, we are primarily concerned with sensitivity for 3P and PP faults on the line when using voltage supervision in the echo logic. $59Q_{ECHO}$ can be set high if application equation (5) is not satisfied, which results in a reduction of sensitivity for line PP faults. If (5) is satisfied, then $59Q_{ECHO}$ will be set relatively low. We consider following the parameters in which (5) will not be satisfied:

- $Z_{TAP} = 1$ pu
- $Z_L = 2$ pu
- $Z_S = 3$ pu

With these parameters for m = 0.5, (5) cannot be satisfied to provide a zone 2 reach in which there is a 1.2 dependability factor for line protection and a 0.8 security factor for low-side bus PG faults. To maintain dependability, k_L is selected as 1.2, which means k_T evaluates to 0.96, rather than the desired 0.8.

For cases in which $k_{T(PG)}$ is greater than 0.8, the $59Q_{ECHO}$ threshold can be found by placing a PP fault on the low-side bus for the system with weakest source, and remote end open ($VQ_{R[PP]}$). This leads to a setting value that exceeds 0.5 pu V2 value and $59Q_{ECHO}$ no longer provides dependability for PP faults on the line. This means dependability is provided via $27PP_{ECHO}$.

The effective Rf coverage for PP faults is shown for this case in Fig. 17. The black circle is the zone 2 characteristic. The green dotted line represents the area of zone 2 that will be permitted to operate with $27PP_{ECHO}$. This is also the effective characteristic for 3P faults. The red circle is the zone 1 characteristic, and it shows that even though the zone 2 Rf coverage is reduced by adding VSUP to the echo logic, the zone 1 still provides sufficient Rf coverage. This is because the tap point is away from the local terminal (at m = 0.5), so zone 1 is set equal to 80 percent of line impedance.

If we make m = 0, even though (5) is still not satisfied ($k_{T[PG]} = 1.6$) the $59Q_{ECHO}$, shown with a dotted blue line, provides improved Rf coverage (see Fig. 17). This makes sense because the V2 voltage at the tap point starts decreasing for the low-side fault as the tap point moves towards the closed line terminal, hence the pickup for $59Q_{ECHO}$ starts decreasing at the remote terminal relay. In this case, the Rf coverage of zone 1 reduces because the tap point is very close (m = 0). Zone 1 reach is reduced and set equal to 80 percent of the tapped transformer impedance.

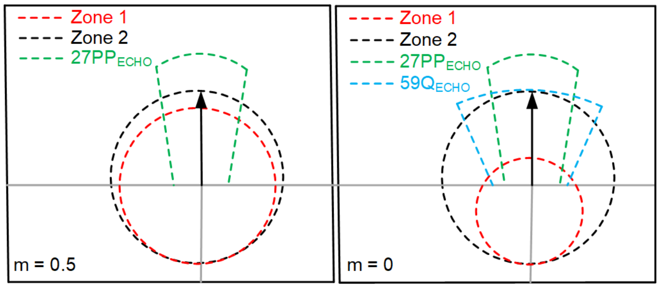

Fig. 17. Maximum sensitivity for PP line faults.

If we shorten the line impedance Z_L from 2 pu to 1 pu and keep m = 0, we now satisfy (5) ($k_{T[PG]} = 0.8$), and maximum sensitivity can be achieved, as shown in Fig. 18. $59Q_{ECHO}$ does not penalize PP fault coverage when (5) is satisfied.

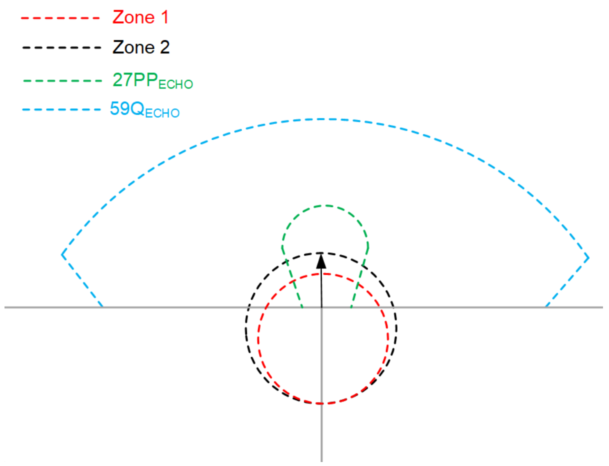

Fig. 18. Maximum sensitivity for PP line faults.

3P faults rely on $27ABC_{ECHO}$, which is set equivalent to $27PP_{ECHO}$. The green dotted line in Fig. 17 represents the Rf coverage for 21P supervised by $27ABC_{ECHO}$ for 3P faults. In applications in which (5) is true, only 3P Rf coverage is reduced. To provide resistive coverage, especially for 3P faults, use a phase time-overcurrent element that coordinates with transformer overcurrent relaying.

B. *Effect of Load*

A PP fault on the low side of an unloaded Dyn transformer produces the highest V2 measured at the open line terminal. As the transformer becomes heavily loaded, V2 reduces, which does not hinder security, even though the distance element may overreach. To illustrate, see Fig. 19.

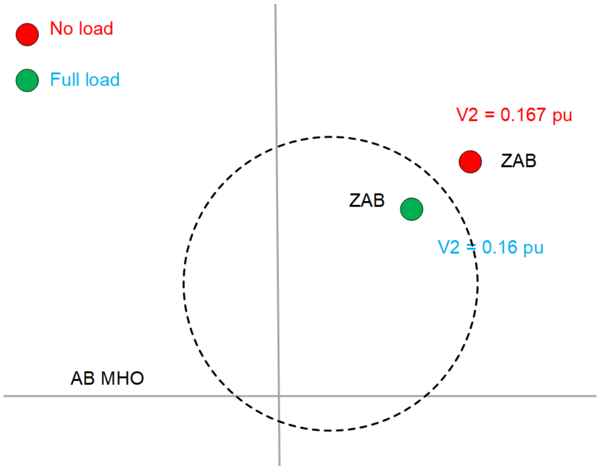

Fig. 19. Effect of load for low-side bus AB fault.

In Fig. 19 we simulate a transformer tapped at $m = 0$, $Z_L = Z_{TAP} = 1$ pu and $Z_S = 0.5$ pu. This is the Z_S value used to set $59Q_{ECHO}$ threshold at 0.2 • VNOM. Lower Z_s will result in less V2 measured at remote terminal, and higher Z_s will result in higher reach requirement for low-side bus PP faults. This is discussed further in Appendices C and E.

For a low-side bus AB fault with no load, ZAB falls outside the mho circle for this case, and the V2 measured at the remote terminal is 0.167 • VNOM, which is below the $59Q_{ECHO}$ setting of 0.2 • VNOM. If a low-side bus PP fault occurs under a full-load condition, the 21P will operate as ZAB falls inside the mho circle, but echo logic with VSUP is still prevented because the V2 measured at the remote terminal during full load is even lower than a no-load condition (0.16 • VNOM).

This shows that load may reduce the 21P security, but it will not reduce the echo logic security when applied with VSUP.

XI. APPENDIX C

The reach required by a positive-sequence memory-polarized phase distance element to operate for a low-side bus PP fault is detailed as follows. For this derivation we assume a no-load condition, so ZLOAD = ∞. Fig. 20. shows the sequence connection for a PP fault on the low-side distribution bus.

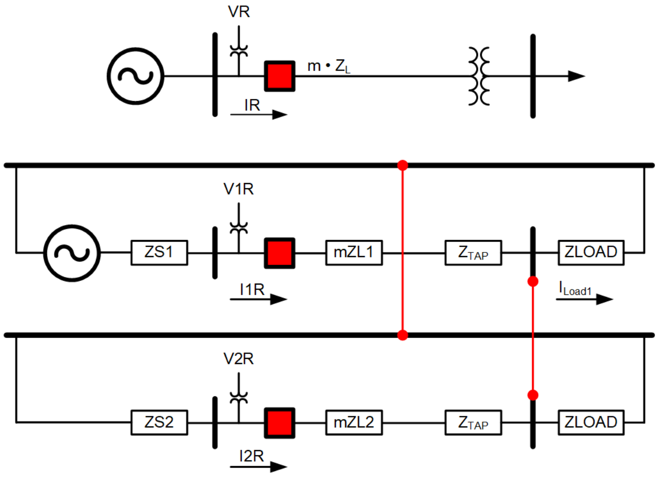

Fig. 20. Sequence connection for low-side distribution bus PP fault.

We define the total positive- and negative-sequence impedance to simplify the definitions for positive-sequence and negative-sequence current (8).

$$\begin{aligned} Z1_{TOT} &= ZS1 + m \bullet ZL1 + ZTAP \\ Z2_{TOT} &= ZS2 + m \bullet ZL2 + ZTAP \end{aligned} \tag{8}$$

We next define the positive- and negative-sequence currents at the relay location. The negative-sequence current is multiplied by $1\angle -60$ to provide the proper phase shift for a Dy1 transformer (9). See [8] for more details.

$$\begin{aligned} I_{1R} &= \frac{1}{Z1_{TOT} + Z2_{TOT}} \\ I_{2R} &= \frac{-1\angle -60}{Z1_{TOT} + Z2_{TOT}} \end{aligned} \tag{9}$$

The positive- and negative-sequence voltages at the relay location (10):

$$\begin{aligned} V_{1R} &= \frac{2 \bullet (m \bullet ZL1 + ZTAP) + ZS1}{Z1_{TOT} + Z2_{TOT}} \\ V_{2R} &= \frac{1\angle -60 \bullet ZS1}{Z1_{TOT} + Z2_{TOT}} \end{aligned} \tag{10}$$

We are interested in the AB loop performance for a low-side BC fault. We define IAB and VAB in terms of sequence components (11):

$$\begin{aligned} I_{AB} &= \sqrt{3}\angle 30 \bullet (I_1 - 1\angle 120 \bullet I_2) \\ V_{AB} &= \sqrt{3}\angle 30 \bullet (V_1 - 1\angle 120 \bullet V_2) \end{aligned} \tag{11}$$

A positive-sequence memory-polarized AB element is defined in (12). We assume the element is fully memorized, so SPOL is defined as the VAB nominal voltage. If T is greater than zero, then the distance element operates:

$$\begin{aligned} &SOP = I_{AB} \bullet Zreach - V_{AB} \\ &SPOL = \sqrt{3}\angle 30 \\ &T = RE\left[SOP \bullet SPOL^{*}\right] \end{aligned} \tag{12}$$

By dividing SOP and SPOL √3 ∠ 30, we can simply solve for the Zreach that will produce T = 0 (the balance point of operation) (13).

$$\begin{aligned} &SOP = \frac{I_{AB}}{\sqrt{3}\angle 30} \bullet Zreach - \frac{V_{AB}}{\sqrt{3}\angle 30} \\ &SPOL = 1\angle 0 \\ &T = RE\left[SOP\right] \end{aligned} \tag{13}$$

With this in mind, we plug in I1R and I2R into IAB and divide by √3 ∠ 30 to get (14):

$$\begin{aligned} \frac{I_{AB}}{\sqrt{3}\angle 30} &= \frac{\sqrt{3}\angle 30}{Z1_{TOT} + Z2_{TOT}} \\ \frac{V_{AB}}{\sqrt{3}\angle 30} &= \frac{2 \bullet (m \bullet ZL1 + TAP) + 1\angle -60 \bullet ZS1}{Z1_{TOT} + Z2_{TOT}} \end{aligned} \tag{14}$$

We then plug these values into SOP and solve for T = 0 to get (15):

$$\begin{aligned} &0 = RE\left[\left(\frac{\sqrt{3}\angle 30}{Z1_{TOT} + Z2_{TOT}}\right) \bullet Zreach - \left(\frac{2 \bullet (m \bullet ZL1 + ZTAP) + 1\angle -60 \bullet ZS1}{Z1_{TOT} + Z2_{TOT}}\right)\right] \\ &Zreach = \frac{4}{3} \bullet (m \bullet Z_{L1} + Z_{TAP}) + \frac{Z_{S1}}{3} \end{aligned} \tag{15}$$

XII. APPENDIX D

The reach required by a positive-sequence memory-polarized phase distance element to operate for a low-side PG fault is detailed as follows. For this derivation we assume a no-load condition, so ZLOAD = ∞. Fig. 21 shows the sequence connection for a PG fault on the low-side distribution bus.

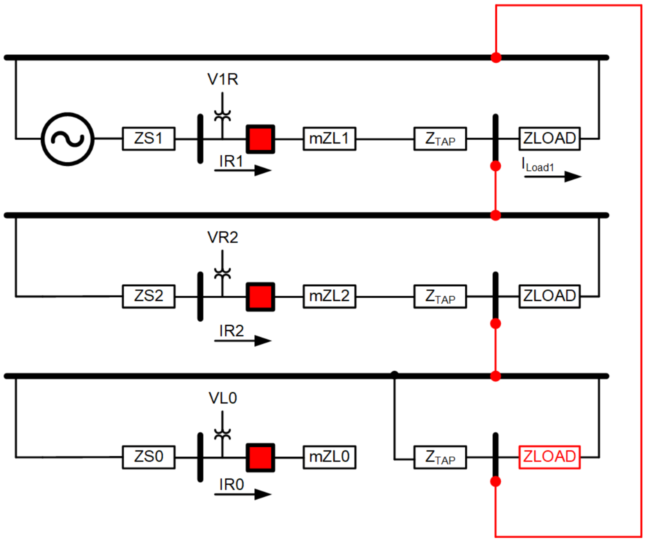

Fig. 21. Sequence connection for low-side distribution bus PG fault.

We define the total positive- and negative-sequence impedance to simplify the definitions for positive-sequence and negative-sequence current (16).

$$\begin{aligned} &Z1_{TOT} = Z2_{TOT} = ZS1 + m \bullet ZL1 + ZTAP \\ &Z0_{TOT} = ZTAP \end{aligned} \tag{16}$$

We next define the positive- and negative-sequence currents at the relay location. The negative-sequence current is multiplied by 1 ∠ –60 to provide the proper phase shift for a Dy1 transformer (17). See [8] for more details.

$$\begin{aligned} I1 &= \frac{1}{2 \bullet Z1_{TOT} + Z0_{TOT}} \\ I2 &= \frac{(1\angle -60)}{2 \bullet Z1_{TOT} + Z0_{TOT}} \end{aligned} \tag{17}$$

The positive- and negative-sequence voltages at the relay location (18):

$$\begin{aligned} V_{1R} &= \frac{2 \bullet Z1_{TOT} + Z0_{TOT} - ZS1}{2 \bullet Z1_{TOT} + Z0_{TOT}} \\ V_{2R} &= -\frac{ZS1 \bullet 1\angle -60}{2 \bullet Z1_{TOT} + Z0_{TOT}} \end{aligned} \tag{18}$$

We are interested in the CA loop performance for a low-side AG fault. We define ICA and VCA in terms of sequence components (19):

$$\begin{aligned} I_{CA} &= \sqrt{3}\angle 150 \bullet (I_1 - 1\angle -120 \bullet I_2) \\ V_{CA} &= \sqrt{3}\angle 150 \bullet (V_1 - 1\angle -120 \bullet V_2) \end{aligned} \tag{19}$$

A positive-sequence memory-polarized CA element is defined by the following three equations (20). We assume the element is fully memorized, so SPOL is defined as the VCA nominal voltage. If T is greater than zero, then the distance element operates:

$$\begin{aligned} &SOP = I_{CA} \bullet Zreach - V_{CA} \\ &SPOL = \sqrt{3}\angle 150 \\ &T = RE\left[SOP \bullet SPOL^{*}\right] \end{aligned} \tag{20}$$

By dividing SOP and SPOL by √3 ∠ 30, we can simply solve for the Zreach that will produce T = 0 (the balance point of operation) (21).

$$\begin{aligned} &SOP = \frac{I_{CA}}{\sqrt{3}\angle 150} \bullet Zreach - \frac{V_{CA}}{\sqrt{3}\angle 150} \\ &SPOL = 1\angle 0 \\ &T = RE\left[SOP\right] \end{aligned} \tag{21}$$

With this in mind, we plug in I1R and I2R into ICA and divide by √3 ∠ 150 to get (22):

$$\begin{aligned} &\frac{I_{CA}}{\sqrt{3}\angle 150} = \frac{2}{2 \bullet Z1_{TOT} + Z0_{TOT}} \\ &\frac{V_{CA}}{\sqrt{3}\angle 150} = \frac{2 \bullet (m \bullet ZL1 + ZTAP) + Z0_{TOT}}{2 \bullet Z1_{TOT} + Z0_{TOT}} \end{aligned} \tag{22}$$

We then plug these values into SOP and solve for T = 0 to get (23):

$$\begin{aligned} &0 = RE\left[\frac{2}{2 \bullet Z1_{TOT} + Z0_{TOT}} \bullet Zreach - \frac{2 \bullet (m \bullet ZL1 + ZTAP) + Z0_{TOT}}{2 \bullet Z1_{TOT} + Z0_{TOT}}\right] \\ &Zreach = m \bullet ZL1 + ZTAP + \frac{1}{2} \bullet Z0_{TOT} \end{aligned} \tag{23}$$

Assuming the transformer zero-sequence impedance is equal to the positive-sequence impedance, we get (24):

$$Zreach = m \bullet ZL1 + 1.5 \bullet ZTAP \tag{24}$$

XIII. APPENDIX E

All unbalanced fault types on the low-side distribution bus of the Dyn and Ydn transformer will produce V2 voltage. A PP fault will produce the highest voltage, PG slightly lower, and PPG the lowest. If we can ensure that zone 2 does not overreach for low-side distribution bus PP faults, we can set $59Q_{ECHO}$ more sensitively than if zone 2 does overreach for low-side PP faults. Ideally, we want to find a dependable and secure setting that does not require much additional work for the relay settings engineer.

First, we start by ensuring the relay does not overreach for PG faults. Evaluate (5) with $k_L = 1.2$. If $k_{T(PG)}$ is less than or equal to 0.8, then the 21P element will have adequate dependability for line faults as well as adequate security for low-side bus PG faults.

$$k_{T(PG)} \le \frac{k_L}{m + 1.5 \bullet \frac{Z_{TAP}}{Z_L}} \tag{5}$$

From Table I, with m = 0, and $Z_L = Z_{TAP}$=1 pu, the relay operates if the zone 2 reach is set to 1.5 • Z_{TAP} for a low-side distribution bus PG fault. If the relay is set with a k_L=1.2, this provides a 20 percent security margin for a low-side distribution bus PG fault. If $Z_L < Z_{TAP}$, then the security margin will increase, and if $Z_L > Z_{TAP}$, then the security margin will decrease. If we want an equivalent security margin of 20 percent for PP faults on the low side bus when (5) is satisfied, the reach required to operate a for a low-side bus PP fault must also be 1.5 • Z_{TAP} when m = 0 and $Z_L = Z_{TAP}$=1. This is shown in (25), and using the apparent reach for PP faults as derived in Appendix C.

$$1.5 = \frac{4}{3} \bullet 1 + \frac{Z_S}{3} \tag{25}$$

We can set $59Q_{ECHO}$ at 0.2 • VNOM to have security for all fault types if (5) is satisfied. If the source impedance is smaller than 0.5 pu, then $59Q_{ECHO}$ will not assert for low-side distribution bus PP faults, maintaining security. If the source impedance is larger than 0.5 pu, 21P becomes more secure for the low-side faults and has no reliance on $59Q_{ECHO}$ to maintain security. 21P may assert for low-side PPG faults because we do not limit the reach based on the apparent impedance seen for a low-side PPG fault. However, $59Q_{ECHO}$ will never exceed a V2 value of 0.2 pu for a low-side distribution bus PPG fault, regardless of system strength (see Fig. 22). This ensures security for low-side distribution bus PPG faults.

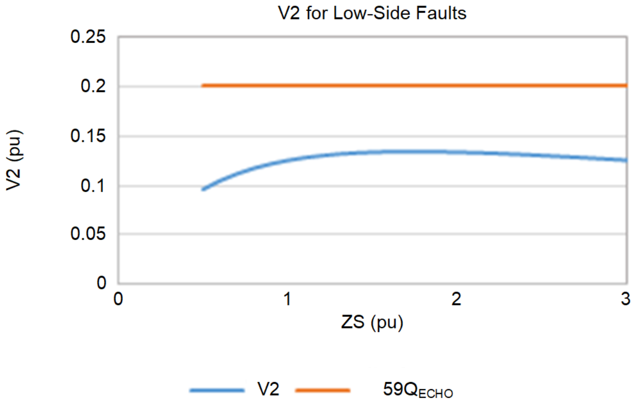

Fig. 22. V2 for PPG faults on the low side for various source impedance (Z_S).

Satisfying (5) provides security for low-side faults with easy-to-apply settings. $59G_{ECHO}$ and $59Q_{ECHO}$ can be set based on VNOM, meaning only $27ABC_{ECHO}$ requires additional work to determine an appropriate setting. We showed in Appendix B.A that these settings also provide excellent sensitivity for line faults.

If (5) is not satisfied, the highest VQ_R can be found by placing a PP fault on the low-side bus for the system with weakest source, and remote end open ($VQ_{R[PP]}$).

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XV. BIOGRAPHIES

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